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Governor design for hydropower plants by intelligent sliding mode variable structure control

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Abstract
This work proposes a neural-fuzzy sliding mode control scheme for a hydro-turbine speed governor system. Considering the assumption of elastic water hammer, a nonlinear mode of the hydro-turbine governor system is established. By linearizing this mode, a sliding mode controller is designed. The linearized mode is subject to uncertainties. The uncertainties are generated in the process of linearization. A radial basis function (RBF) neural network is introduced to compensate for the uncertainties. The update formulas for the neural networks are derived from the Lyapunov direct method. For the chattering phenomenon of the sliding mode control, a fuzzy logic inference system is adopted. In the sense of Lyapunov, the asymptotical stability of the system can be guaranteed. Compared with the internal mode control and the conventional PID control method, some numerical simulations verify the feasibility and robustness of the proposed scheme.

Keywords: *Hydropower Plant, Speed Governor, Water Hammer, Neural Network, Fuzzy Logic, Sliding Mode Control, Chattering.*

1. Introduction

With the increasing acute global energy crisis, hydropower, an ideal renewable and clean energy, has been given a widely social concern. It is generally known that the hydropower generation has a great development potential and a broad market prospect. A hydro-turbine governor system is an important part of the hydropower plants [1], and the speed governor plays a vital role in controlling the hydro-turbine speed. Therefore, research work on the hydro-turbine governor system has becomes significant.

A hydro-turbine governor system is a complex nonlinear object, which features time- variant and non-minimum phases. For the non- linear governor system, various mathematical models and control methods have been presented.

Many different mathematical models have been proposed in terms of the hydropower plants. For example, Paolo [2] has presented a detailed numerical model for the dynamic behavior of the Francis turbine, and has considered the effects of water hammer on the turbine. Chen [3] has introduced a novel model of a hydro-turbine system with a surge tank, and has studied the non-linear dynamical behaviors of the hydro-turbine system.

According to many different mathematical models, various control methods have been proposed. Tan [4] has designed a PID tuning of load frequency controller based on a two-degree-of-freedom internal model control. Using a high-gain observer to replace the coordinate transformation, Liu [5] has presented a nonlinear robust control strategy, which is only required to measure the rotor speed. Kishor [6] has used the H-infinity method to approximate the non-linear part of the penstock-turbine transfer function, and has studied the hydraulic transient characteristics. Qian [7] has presented a GA- based fuzzy sliding mode control approach for speed governing of a hydro-turbine. Most of the methods mentioned above only focus on the accurate linear model and the non-linear dynamical analysis. However, few papers have paid attention to the uncertainties generated in the process of linearization of the non-linear mode, and the influence of elastic water hammer upon the security and stability of a hydro-turbine governor system.

In order to further investigate the hydro -turbine governor system, a novel non-linear mathematical model with elastic water hammer was developed. By linearizing the nonlinear mode, the sliding mode controller was designed. The advantage of the sliding mode control method is that in the sliding motion, the designed controller shows strong robustness and high control accuracy in the presence of uncertainties and external disturbances. However, the designed sliding mode controller based on the linearized model cannot stabilize the non-linear governor system. Furthermore, a chattering phenomenon [8] exists in the conventional sliding mode control method. Therefore, in this work, we presented a neural-fuzzy sliding mode control scheme, which combines with the merits of the fuzzy set theory [9-10], neural networks [11-12], and sliding mode control [13-14]. A radial basis function (RBF) neural network was introduced to compensate for the uncertainties generated in the process of linearization of the non-linear mode [15]. The update formula of the network was deduced from the Lyapunov direct method so that the weight convergence and system stability could be simultaneously guaranteed. Considering the chattering phenomenon of the sliding mode control, a fuzzy logic inference system was adopted to regulate the gain of the switching control law according to the system performance [16]. In the sense of Lyapunov, the asymptotically stability of the whole system could be guaranteed. The simulation results obtained demonstrated the effectiveness of the proposed scheme to improve the dynamic performance of the system and attenuate the chattering phenomenon.

This paper is organized as follows. Under the assumption of elastic water hammer, the detailed nonlinear mathematical model of a hydro-turbine governor system is given in Section 2. The design of a new neural-fuzzy sliding mode controller is reported in Section 3. The simulation results for the different states in the hydro-turbine governor system are illustrated in Section 4. Finally, conclusions are given in Section 5.

2. Mode of hydro-turbine governor system

2.1 Penstock and hydro-turbine

When penstocks are short or medium in length, the hydraulic turbine model is adequate under the assumption of the inelasticity of penstocks and the incompressibility of fluid. However, considering the hydropower plants with long conduits, it has to take into account the effects of elasticity of penstock and compressibility of fluid. Water hammer is produced by the rapid velocity changes of the flowing fluid in the pipelines. The emergence of elastic water hammer can cause serious problems for the hydraulic turbine, and then affects the whole power system. Therefore, the stability study of the hydroelectric power plant with elastic water hammer is of paramount importance. In this paper, the mathematical models of the water tunnel and penstock components are presented under the assumption of elastic water hammer. The elastic water hammer is represented by a delay block of e^{-Trs}. Three components interconnected with each other constitute the nonlinear governing system, as shown in figure 1.

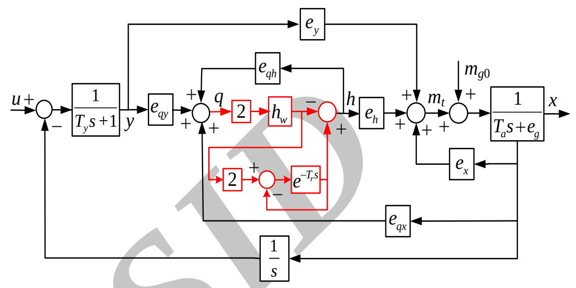

Figure 1. Transfer function block diagram of a hydro-turbine governor system.

Considering a small variation around an operating point, the linearized equation of the Francis hydro-turbine can be given as

$$\begin{aligned} m_t &= e_x x + e_y y + e_h h \\ q &= e_{qx} x + e_{qy} y + e_{qh} h \end{aligned} \qquad (1)$$

The six hydro-turbine constants e_x, e_y, e_h, e_{qx}, e_{qy}, and e_{qh} can be defined as:

$$e_x = \frac{\partial m_t}{\partial x}, e_y = \frac{\partial m_t}{\partial y}, e_h = \frac{\partial m_t}{\partial h}, e_{qx} = \frac{\partial q}{\partial x}, e_{qy} = \frac{\partial q}{\partial y}, e_{qh} = \frac{\partial q}{\partial h}$$

The effects of surge tank are ignored, and the transfer function of penstock with the incremental head and flow can be written as

$$\frac{\Delta h(s)}{\Delta q(s)} = -2h_w th(0.5T_r s) \qquad (2)$$

Compared with the traditional simplified method of the Taylor series expansion, this paper presents a new simplified nonlinear method, as shown in function (3).

When the hyperbolic tangent function is converted to an exponential function, the transfer function of penstock with the incremental head and flow can be given as

$$\begin{aligned} G_h(s) &= \frac{\Delta h(s)}{\Delta q(s)} = -2h_w th(0.5T_r s) \\ &= -2h_w (1 - 2\frac{e^{-T_r s}}{1+e^{-T_r s}}) \end{aligned} \qquad (3)$$

The new method takes into accounts the higher order terms of the system model. Therefore, the accuracies of the hydraulic tunnel and the penstock are greatly improved. In figure 1, the red section means the hydraulic turbine part taking elastic water hammer; this relation only depends on the length of penstock. Considering the elastic water hammer, the hydro-turbine transfer function relating to the mechanical power and the wicket gate opening can be derived and written as

$$\frac{\Delta m_t(s)}{\Delta y(s)} = e_y \frac{1-2h_w e \tanh(0.5T_r s)}{1+2h_w e_{qh} \tanh(0.5T_r s)} \quad (4)$$

where, $e=e_{qy}e_h/e_y-e_q$, and h_w is the normalized hydraulic impedance of penstock, the water inertia time is $T_w=T_r h_w$, the penstock reflection time is $T_r=2L/a$, penstock length is L, and the water wave velocity is a.

2.2 Wicket gate and servomechanism

The servomotor is used to amplify the control signal, and to provide power to operate the guide vane. Neglecting small time constants, the transfer function relating to the control signal u and the wicket gate servomotor stroke y can be written as:

$$\frac{\Delta y(s)}{\Delta u(s)} = \frac{1}{T_y s+1} \quad (5)$$

where, T_y is the response time of the wicket gate servomotor

2.3 Generator and network

If the generator unit supplies for an isolated load, the dynamic process of the synchronous generator unit only relating to the moment of inertia can be described as

$$\frac{\Delta x(s)}{\Delta[(m_t - m_{g0})(s)]} = \frac{1}{T_a s + e_g} \quad (6)$$

where, m_t is the turbine torque (in per unit), m_{g0} is the load torque (in per unit), T_a is the generator unit mechanical time (in seconds), and e_g is the load self-regulation fact.

3. Control designed and analysis

3.1 Design of RBF network-based sliding mode controller

Taking into account the linearized small-signal model of an ideal Francis turbine, the expression of penstock with inelastic water hammer and non-friction can be obtained by the Taylor series expansion.

$$\frac{\Delta h(s)}{\Delta q(s)} = -2h_w th(0.5T_r s) = -T_w s \quad (7)$$

Thus a 3-order mode of state space is obtained by linearization of the simplified model, where the system state variables are independent and measurable. The wicket gate servomotor stroke relative deviation $x_3=y$, the turbine torque relative deviation $x_2=m_t$ and the turbine speed relative deviation $x_1=x$. To eliminate the speed deviation, the integral of x_1 is utilized as an additional state x_4, which is defined as

$$x_4 = \int_0^\infty x_1 dt \quad (8)$$

The state space expression for the hydro-turbine governor system with model uncertainties and external disturbances is described as follows.

$$\begin{aligned} \dot{x} &= (A+\Delta A)x + (B+\Delta B)u + F(d(t)+g(t)) \\ &= Ax + Bu + f \\ y &= C^T x \end{aligned} \quad (9)$$

where, $x=[x_1\ x_2\ x_3\ x_4]^T$ is the state vector; ΔA and ΔB are unknown or uncertain; $d(t)$ values are disturbances including the parameter variations and load disturbances; $g(t)$ is the external indefinite disturbance; f is the uncertainties consisting of all unknown parts and disturbances; and $C^T=[1\ 0\ 0\ 0]$ is the output matrix.

$$A = \begin{bmatrix} -\frac{e_g - e_x}{T_a} & \frac{1}{T_a} & 0 & 0 \\ 0 & -\frac{1}{e_{qh}T_w} & \frac{e_{qy}e_h - e_{qh}e_y}{T_y e_{qh}} + \frac{e_y}{e_{qh}T_w} & \frac{e_{qy}e_h - e_{qh}e_y}{T_y e_{qh}} \\ 0 & 0 & -\frac{1}{T_y} & -\frac{1}{T_y} \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

$$B = [0 \quad -\frac{e_{qy}e_h - e_{qh}e_y}{T_y e_{qh}} \quad \frac{1}{T_y} \quad 0]^T$$

$$F = [\frac{1}{T_a} \quad 0 \quad 0 \quad 0]^T$$

$$f = \Delta Ax + \Delta Bu + F(d(t)+g(t))$$

The sliding mode controller consists of two stages. First the sliding surface is defined as

$$s = c^T x = c_1 x_1 + c_2 x_2 + c_3 x_3 + c_4 x_4 \quad (10)$$

where, c_i (i=1,2,3,4) is the sliding surface coefficient vector, which is positive constant.

Secondly, the sliding mode control law is designed, which is composed of the equivalent control law and the switching control law

$$u = u_{eq} + u_{sw} \quad (11)$$

where, u_{eq} forces the system trajectory to the sliding mode stage, and is defined as the equivalent control law. u_{sw} keeps the system trajectory on the sliding surface and is defined as the switching control law.

Furthermore, u_{eq} can be obtained by

$$\dot{s} = c^T \dot{x} = 0 \quad (12)$$

Substituting (8) into (12) yields

$$u_{eq} = -(c^T B)^{-1} c^T Ax \quad (13)$$

Take into account the following positive definite function as a Lyapunov candidate function:

$$V(t)=\frac{1}{2}s^2 \tag{14}$$

Differentiating $V(t)$ with respect to time t yields:

$$\begin{aligned}\dot{V}(t)&=s\dot{s}\\&=s[c^T\dot{x}]\\&=s[c^T(Ax+Bu+f)]\\&=s[c^T(Ax+Bu_{eq})+c^TBu_{sw}+c^Tf]\\&=s[c^TBu_{sw}+c^Tf]\end{aligned} \tag{15}$$

The switching control is obtained as:

$$u_{sw}=-(c^TB)^{-1}[ks+\eta sign(s)] \tag{16}$$

where, η, k are positive constants.
Substituting (16) into (15) yields:

$$\dot{V}(t)=-ks^2-\eta|s|+c^Tfs\le -ks^2-(\eta-|c^Tf|)|s| \tag{17}$$

where, $\eta=\eta_0+c^T\overline{f}$, and η_0 is positive constant. If the upper bound of the uncertain parts $c^T\overline{f}=\sup c^Tf$ is certainty, it can judge the stability of the system by using the Lyapunov stability theory.
Considering the influence of uncertainties on the stability and robustness of the system, a RBF neural network is adopted to approximate the uncertainties. The system state vector x is defined as the network input, and $\hat{f}$ is the estimated f value as the network output. The update formula of the network can be deduced using the Lyapunov direct method.

$$\hat{f}(x)=W^Th(x) \tag{18}$$

$$f(x)=W^{*T}h(x)+\varepsilon \tag{19}$$

where, W is the weight matrix of the RBF neural network, and W^* is the optimal weight of the RBF neural network; ε is the approximation error of the RBF neural network, and $h(x)$ is the radial basis function, which it is determined by:

$$h(x)=\exp\left(\frac{\|x-c_f\|^2}{2b_f^2}\right) \tag{20}$$

where, c_f and b_f depict the center and width of the hidden neuron of the RBF network. We can make the following assumptions:

1. There exists an optimal weight W^*, so that the output of the optimal network satisfies $c^T|W^{*T}h(x)-\overline{f}|\le\varepsilon_0$, where ε_0 is a positive constant.
2. The norm of the system uncertainties and its upper bound satisfy the following relationship $c^T|\overline{f}-f|\ge\varepsilon_1\ge\varepsilon_0$, where ε_1 is a positive constant.

To get the update formulas, a new Lyapunov function is needed to redefine, as follows:

$$V(t)=\frac{1}{2}s^2+\frac{1}{2}\alpha^{-1}\hat{W}^T\hat{W} \tag{21}$$

where, $\hat{W}=W^*-W$, $\dot{\hat{W}}=-\dot{W}$, and α is a positive constant.
Differentiating $V(t)$ with respect to time t yields:

$$\dot{V}(\mathrm{t})=s\dot{s}+\alpha^{-1}\hat{W}^T\dot{\hat{W}} \tag{22}$$

The adaptive law of RBF network is defined as:

$$\dot{W}=c^T\alpha|s|h(x) \tag{23}$$

By substituting (17) and (23) into (22), $\dot{V}(t)$ is obtained as:

$$\begin{aligned}\dot{V}(t)&=s\dot{s}-\alpha^{-1}(W^*-W)^T\dot{W}\\&=s[-ks-(\eta-c^T\hat{f})sgn(s)]-\alpha^{-1}(W^*-W)^Tc^T\alpha h(x)|s|\\&=s[-ks-(\eta-c^T\hat{f})sgn(s)]-\alpha^{-1}[W^{*\mathrm{T}}\exp\left(\frac{\|x-c_f\|^2}{2b_f^2}\right)\\&\quad-W^T\exp\left(\frac{\|x-c_f\|^2}{2b_f^2}\right)]c^T\alpha|s|\\&\le -ks^2-\eta_0|s|-c^T(\overline{f}-\hat{f})|s|\\&\quad-c^T(W^{*T}\exp\left(\frac{\|x-c_f\|^2}{2b_f^2}\right)-|f|)|s|\\&\le -ks^2-\eta_0|s|-(\varepsilon_1-\varepsilon_0)|s|\end{aligned} \tag{24}$$

According to the assumptions 1 and 2, the Lyapunov function (22) satisfies $\dot{V}(\mathrm{t})\le 0$, i.e. the system (9) with the uncertainties is asymptotic stability in the sense of Lyapunov once the control law (11) is adopted.

3.2 Design of fuzzy sliding mode controller

Although the sliding mode control is one of the effective non-linear control approaches, its drawback is the chattering phenomenon, which is determined by the switching function and its gain. To solve this chattering problem, the key is how to minimize reasonably the switching control signal. Therefore, a fuzzy logic inference system is introduced to regulate the gain of the switching control law to alleviate the chattering problem.
The design of a fuzzy logic controller having one input and one output was proposed. The number of fuzzy control rules can be minimized since only one input variable s. As mentioned earlier in Section 2, u_{eq} is the equivalent control law, and u_{sw} is the switching control law. The fuzzy control rules can be expressed as follow:

I. If s is ZO, then u is u_{eq} .
II. If s is NZ, then u is $u_{eq}+u_{sw}$.

where the fuzzy sets ZO and NZ represent zero and non-zero， and the sliding surface variable *s* is the input of the fuzzy controller. When the *s* value is zero, then the control law of the fuzzy sliding mode controller is only determined by the equivalent control. Similarly, when the *s* value is non-zero, then that is composed of the equivalent control and the switching control.

However, in practice application, only two control rules cannot be enough to completely describe the operation of a non-linear hydro-turbine governor system. In order to eliminate this weakness and attenuate the chattering phenomena simultaneously, five items of fuzzy rules based on the theory of sliding mode control were presented by incorporating the fuzzy logic control.

The fuzzy logic system can be briefly described as follows. The sliding surface variable *s* is regarded as the input of fuzzy controller, and the weighting of the switching control law *w*1 is chosen as the output of fuzzy controller. The fuzzy control rules are designed according to the operation experiences. By fusing the prior knowledge about the sliding mode control, we know that when the system states are far from the sliding surface, a large *w*1 value is needed. Otherwise, a small *w*1 value is required. To determine the final control action, the fuzzy rules can be designed as follow:

I. If *s* is PB, then *w*1 is PB.
II. If *s* is PM, then *w*1 is PM.
III. If *s* is ZO, then *w*1 is ZO.
IV. If *s* is NM, then *w*1 is PM.
V. If *s* is NB, then *w*1 is PB.

where, NB, NM, ZO, PM, and PB are negative big, negative medium, zero, positive medium, and positive big, respectively. Figure 2 shows the membership functions of the linguistic labels NB, NM, ZO, PM, and PB for the term *s*, and the membership functions of the linguistic labels NB, NM, ZO, PM, and PB for *w*1. The output of the designed fuzzy inference system is shown in figure 3. Finally, the output of the fuzzy controller *w*1 can be obtained by the output singleton fuzzy sets and the center-of-gravity defuzzification method.

The final value of the switching law by the fuzzy logic law is defined as:

$$u'_{sw} = w1 \times u_{sw} \tag{24}$$

The final total control law *u* is obtained as:

$$u = u_{eq} + w1 \times u_{sw} \tag{25}$$

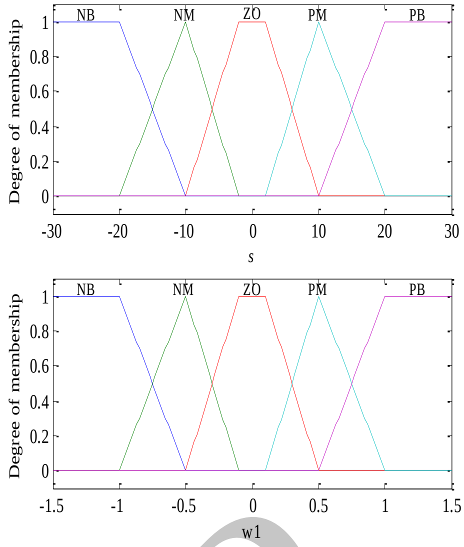

Figure 2. Membership functions of *s* and *w*1.

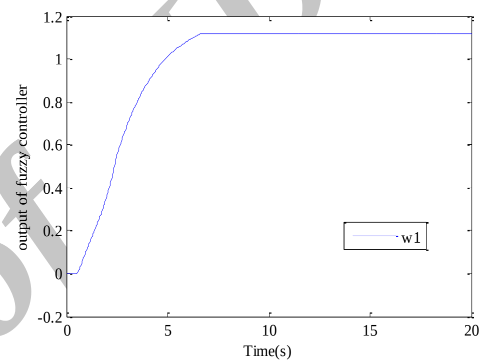

Figure 3. Output surface of the fuzzy interface system.

4. Numerical simulation

The hydro-turbine governor system was supplied for an isolated network with a single-penstock /single-Francis turbine. The parameters of the hydropower plant were defined as T_r=2, h_w=0.55, T_y=0.5, and T_a=6.65. Table 1 shows the time-varying transferred coefficients of the hydro-turbine governor system, and the initial states $x_0=[0\ 0\ 0\ 0]^T$. The parameters for the sliding surface *s* were chosen to be c_1=50.39, c_2=3.32, c_3=6.74, and c_4=22.4 from Acker command of MATLAB by placing the pole of Ackermann's formula in the vector [−1 −2−2i −2+2i −8].

The center c_f and width b_f of the hidden neuron of the RBF network were designed as random numbers in the interval (0, 1). The parameter α was selected to be 10^8. n^* was selected to be 6, which is the number of hidden neurons. The parameters k and η were determined to be k =0.2, η=0.05.

For comparison with the dynamic and steady-state performances of different control methods, we adopted the internal mode control and the conventional PID control.

Table 1. Some coefficients of hydraulic turbine system.

Point	e_x	e_y	e_h	e_{qx}	e_{qy}	e_{qh}	e_g
Case 1	-1.00	1.00	1.50	0.00	1.00	0.50	0.21
Case 2	-0.26	1.92	0.92	0.00	1.06	0.35	0.21

A. Load rejection

To demonstrate the dynamic nonlinear characteristic of the presented scheme, 10% load disturbance was applied as the interference signal. Under the operating condition Case 1, the comparisons among the neural-fuzzy sliding mode control, the internal mode control and the conventional PID control are shown in figure 4. According to this figure, compared with the internal mode control, the overshoot of the state variables with the fuzzy sliding mode control x_1, x_2, x_3 in the hydro-turbine governor system decreased, and the regulation time was greatly shortened. Compared with the conventional PID control, the dynamic performance of the state variables improved significantly, where the regulation time of the controlled system was shortened, the fluctuation times were reduced, and the accuracy of the stable states was improved. According to figure 5, the chattering phenomena of the control input u improved significantly. The numerical simulation results obtained show that the proposed scheme has strong anti-interference and preferable dynamic characteristics.

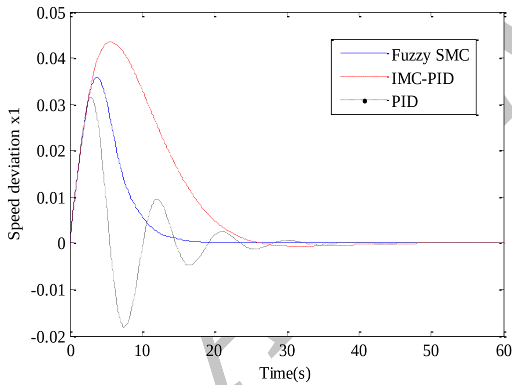

Figure 4(a). Speed deviation x_1.

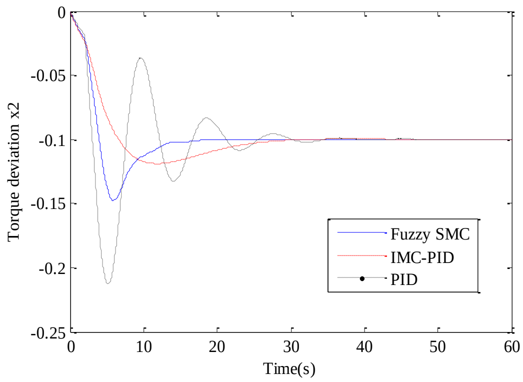

Figure 4(b). Torque deviation x_2.

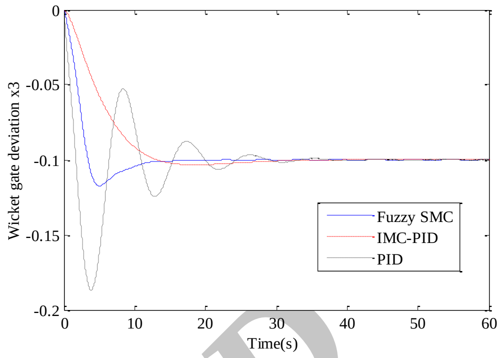

Figure 4(c). Water gate deviation x_3.

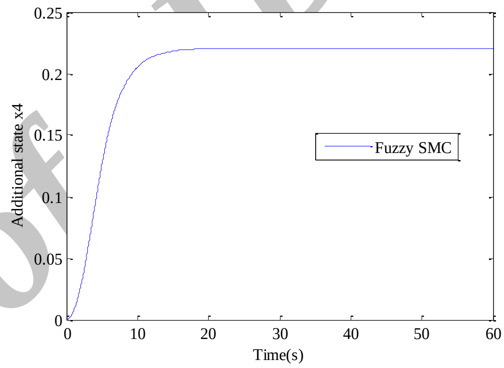

Figure 4(d). Additional state x_4.

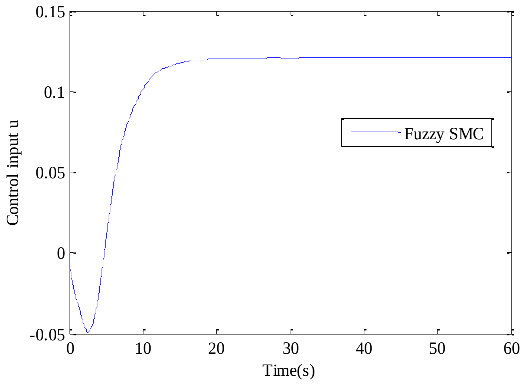

Figure 5. Control input *u*.

B. Robustness testing

In order to verify the robustness of the neural-fuzzy sliding mode governor, 10% of the load rejection under the operating conditions Case 1 and Case 2 was tested. The controller parameters were kept unchanged. According to figure 6, the state variables of the hydro-turbine governor system could still have a good robustness when the system parameters changed. In practical applications, the proposed neural-fuzzy sliding mode governor possesses a great advantage. It can significantly extend the lifetime of equipment and improve the safety and reliability of the hydroelectric power plants.

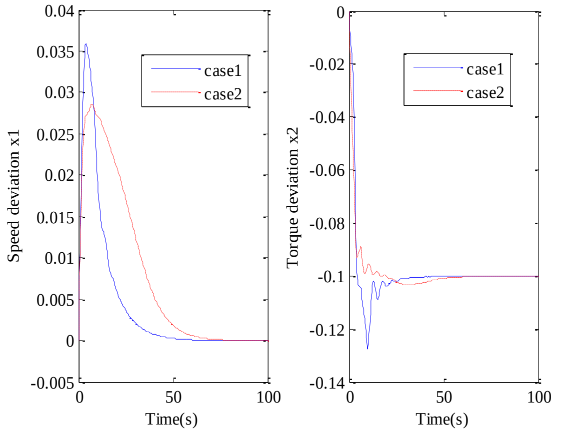

Figure 6(a). Speed deviation x_1 and torque deviation x_2.

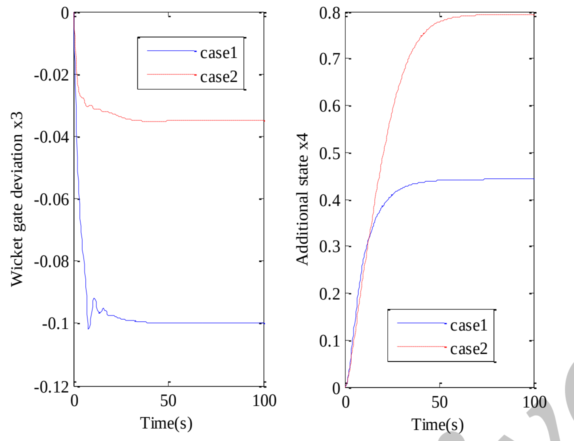

Figure 6(b). Water gate deviation x_3 and additional state x_4.

5. Conclusion

In this work, a novel non-linear mathematical model for a hydro-turbine governor system with elastic water hammer was established. Considering the previous nonlinear systems used to reach an ideal dynamic performance, a neural-fuzzy sliding mode governor was proposed. The non-linear mathematic model for hydropower plants was linearized, and a radial basis function (RBF) neural network was introduced for compensate for the error between the linearized and non-linear models. In order to eliminate the chattering phenomenon, a fuzzy logic inference system was designed to regulate the gain of the switching control law. Compared with the internal mode control and the conventional PID control, the proposed neural-fuzzy sliding mode governor improved the dynamic and steady-state performance of the system. The numerical simulation results demonstrated the feasibility, robustness, and stability of the proposed method.

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نشریه هوش مصنوعی و داده کاوی

دانشگاه شاهرود

طراحی مدار فرمان برای نیروگاه برق آبی توسط کنترل ساختار متغیر حالت لغزان هوشمند

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چکیده:

این تحقیق یک روش کنترل عصبی فازی با حالت لغزان را برای یک سیستم مدیریت سرعت توربین آبی پیشنهاد می‌کند. با توجه به فرض چکش آب الاستیک، یک حالت غیر خطی سیستم فرماندار توربین آبی ایجاد شده است. با خطی سازی این حالت، یک کنترل حالت کشویی طراحی شده است. حالت خطی منوط به عدم قطعیت می‌باشد. عدم قطعیت در روند خطی تولید می‌شود. یک شبکه عصبی تابع پایه شعاعی (RBF) برای جبران عدم قطعیت معرفی شده است. فرمول به روز رسانی شبکه های عصبی از روش مستقیم لیاپانوف استخراج شده است. برای این پدیده چترینگ از کنترل مد لغزشی، یک سیستم استنتاج منطق فازی اتخاذ شده است. در مفهوم لیاپانوف، ثبات مجانبی سیستم می‌تواند تضمین شود. در مقایسه با کنترل حالت داخلی و روش کنترل PID معمولی، برخی از شبیه‌سازی‌های عددی امکان‌سنجی و استحکام طرح پیشنهادی ارائه شده را تأیید می‌کنند.

کلمات کلیدی: .نیروگاه برق آبی، مدیریت سرعت، آب الاستیک، شبکه عصبی، منطق فازی، کنترل حالت لغزان.